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MENTATION PAGE

Form Approved
OMB No. 0704-0188

is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, ng and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this ng this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.

REPORT DATE

3. REPORT TYPE AND DATES COVERED
Final Report 1 Feb 92-31 Jan 93

4. TITLE AND SUBTITLE
Novel Methods of Acceleration

DTIC
ELECTE
MAY 1 4 1993
S C D

5. FUNDING NUMBERS
F49620-93-J-0153

6. AUTHOR(S)
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8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
AFOSR NE
110 Duncan Avenue Suite B115
Bolling AFB DC 20332-0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
2301/ES

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT
UNLIMITED

12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

This report describes work carried out on AFOSR grant number F49620-92-J-0153 DEF during the period February 1 1992 to January 31 1993. The report provides a brief description of the program objectives, summarizes the main accomplishments during the last year and concludes with listings of conferences and refereed publications, which have either been submitted for publications or published during the program year.

93-10653

14. SUBJECT TERMS

15. NUMBER OF PAGES

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

NOVEL METHODS OF ACCELERATION

Final Rpt.

~~ANNUAL~~ REPORT FOR PERIOD FEB 1 1992 TO JAN 31 1993

ON

GRANT F49620-92-J-0153DEF

Prepared by:

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Table of Contents

Introduction 1

Technical Program 1

High Power TWT Amplifier Results 1

Diagnostic Development and Results 2

Theoretical Considerations 4

Electron Beam Modulator 7

Conclusions 8

Refereed Journal and Conference Papers 9

INTRODUCTION

This report describes work carried out on AFOSR grant number F49620-92-J-0153DEF during the period February 1 1992 to January 31 1993. The report provides a brief description of the program objectives, summarizes the main accomplishments during the last year and concludes with listings of conference and refereed publications, which have either been submitted for publication or published during the program year.

TECHNICAL PROGRAM

High Power TWT Amplifier Results

The primary purpose of this research is the development of an intense coherent microwave source in X band and its application to a compact high current electron accelerator suitable for use, for example, as a driver for an FEL.

During the past year and a half our efforts have been mainly devoted to improving the spectral quality of the microwave signal generated by our traveling wave tube amplifiers. Our efforts have lead us to the conclusion that we are more likely to achieve a successful device if we use a two stage amplifier. This conclusion follows since it is very difficult to eliminate reflections from the output of the amplifier, and hence feedback to its input, with eventual onset of oscillation. Towards this goal we have employed a dielectric loaded waveguide amplifier for the first stage followed by a sever, and as described in our last proposal, a very low group velocity TWT amplifier for the second stage. The experiment is shown schematically in fig. 1. The purpose of the first stage is to preamplify our input 30 kW signal by about 20 dB. Following the preamplification we cut off the EM wave in the sever allowing the space charge wave to propagate into the narrow band second stage amplifier. The EM wave rapidly reconstructs and is further amplified. In this way we overcome oscillation due to positive feedback and get a large amplitude wave in the narrow band amplifier section. In practice this procedure was essential as the 30 kW input wave would not enter the narrow band section from a uniform pipe since the reflection coefficient was too high.

The main rationale for use of the narrow band structure (NBS) was to effectively transit time isolate the input from the output and, since the inner diameter of the irises separating each cavity in the amplifier from its neighbor is beyond cut-off, also to achieve significant attenuation of any reflected signal from the output. For the forward amplifying wave the attenuation is unimportant because the electron beam couples successive cavities. Since our last proposal was submitted we have designed, simulated, built, and carried out initial tests on two narrow band second stage amplifiers. Simulation shows that the gain is very high, of the order of 5-6 dB/cm so that only short sections of amplifier are needed. Fig. 2 shows simulation data for one of our devices designed to amplify at about 9 GHz. The phase advance per cell is designed to be 120 degrees and the amplifier has a total bandwidth of only 200 MHz. The output FFT shows that the sideband radiation due to structure resonances has been eliminated. Note that even if feedback were significant the expected bandwidth for electron momentum spreads comparable to the original cold beam momentum would only be about 30 MHz and hence comparable to the natural bandwidth for the electron beam pulse duration. For comparison we also show the FFT from a simulation of one of our earlier amplifiers in which the bandwidth was 1.7 GHz and the gain less than 2 dB per cm. The change in the output rf quality is apparent. In fig. 3 we show similar traces obtained experimentally. The performance of the new NBS is clearly superior and closely matches expectation as regards the rf beam quality.

We have measured the performance of all stages of the two stage amplifier both individually and collectively. The data shown in fig. 4 are representative of the performance of the amplifier at low and high powers. In all cases there is no evidence of pulse shortening or of multiple frequency components in the output signal. Note that the signals have been measured in the far field using a standard gain horn to sample the amplifier output. To obtain this signal it was necessary to modify the output of the amplifier by use of a narrow iris between the amplifier and the uniform guide. More details on this design feature will be presented later in the report . From data of the type presented in fig. 4 we have obtained the frequency response (fig. 5) for the full system. It should be noted that the calorimeter pressure transducer saturates at an incident power level around 65 MW The amplifier shows a narrow band response as expected from calculation and simulation. At the peak output level recorded we estimate the rf power to be close to 200 MW. This figure has been confirmed experimentally using a calorimeter which has been fabricated in the last several months. Details of the design and calibration of the calorimeter are presented later in this report.

<u>Diagnostic Development and Results</u>

Two new diagnostic tools have been used in the research during the last year, namely a multichannel Faraday cup magnetic spectrometer to measure electron energy gain in accelerators, and the calorimeter mentioned above to measure the energy content of amplified rf signals. The calorimeter provides an independent measurement of the rf power level achieved. The magnetic spectrometer was used in this period to attempt to measure the energy spread acquired by the electrons as a result of the interaction in the NBS. Fig. 6 shows energy spectra for two values of deflection field with and without rf power input. At both the high and low energy sides of the spectrum there appears to be an increase in the electron energy spread with rf power on. The resolution of the spectrometer limits any quantitative information on this apparent spreading. It should also be noted that when the rf power is on the total charge collected by the Faraday cup array can be up to a factor of two lower than with no rf input. This result is consistent with low energy particles being deflected through large angles and being lost to the detection system. Analytical studies show that as much as 90% of the original distribution will lose energy during the amplification process.

In the experiments described above we did not compare the results to data in the absence of any structure in the system. Due to the high gain of the NBS amplification starts from noise and can be significant by the end of the amplifier. The very high shunt impedance of the narrow band amplifier results in a strong modulation of the electron momentum for even relatively low powers. We did not recognize this limitation on our null experiment until relatively recently and will have to repeat the experiment without any amplifier present. We are also planning to run new experiments with a fluorescent screen to measure the deflection of the electrons in the spectrometer. This change should allow us to use a lower apertured current and hence obtain less beam divergence and higher accuracy in the electron energy distribution measurement. Designs are also underway for a 180° spectrometer which will have better energy resolution as the electron energy is increased.

The calorimeter use has already been described above and gives us considerably greater confidence in our earlier results. The calorimeter design is based on one originally built by C. Wharton. It relies on absorption of the amplified rf power into a load which is immersed in a gas filled chamber. The change in gas pressure is a direct measure of the energy absorption. The calorimeter is mounted in a four inch diameter pipe which is connected, via a smooth transition to the output of the amplifier. The assembly is shown in fig. 7. The chamber , which contains the space cloth absorber, is sealed by a 1/8th inch lucite plate and filled with either SF_6 or dry air. The pressure change is measured by a pressure transducer which is calibrated against the known power from a 1.5 μsec duration, 250 kW magnetron operated in a repetitive pulse mode. The complete device is shielded in a 1/2 inch thick aluminum box to prevent electrical pickup. Measurements show that the system reflects less than 10% of the incident microwave power over a 400 MHz band centered on the operating 9 GHz frequency. Typical output calibration shots are shown in fig. 8 and the resulting calibration curve in fig. 9. Note that in use we monitor energies of up to 4.5 Joules and hence assume that the system response is linear beyond the calibration data limits set by our available sources. In fact we have monitored the far field radiation intensity as a function of frequency for the amplifier and have confirmed that the far field signal and the calorimeter track at power levels of up to 60 MW. Beyond that the calorimeter saturates (see fig. 5). The saturation level measured is about 50% of the saturation level quoted for the transducer. We have however, from this set of measurements, obtained confidence that the peak power levels are within about 1 or 2 dB of the levels quoted, and that the far field measurement technique provides a reliable measurement of the radiated power.

Theoretical Considerations

Amplifier Oscillator: A Unified Study

The experimental results on high power microwave generation in the past years indicates that power levels from two stage amplifier could reach $450MW$ with an efficiency of almost 50% albeit with an output spectrum width of more than $300MHz$. In fact about 50% of this power occurred in sidebands which were *asymmetric* relative to the frequency of the input signal - ruling out the possibility of a non-linear effect being responsible to their occurrence. This kind of output is inadequate for acceleration purposes. Theoretical studies of the sidebands has indicated that they are result of three simultaneous processes in the amplifier: (i) large velocity spread in the interaction process which induces in the system a broad noise spectrum according to the electromagnetic characteristic of the slow wave structure. (ii) This electromagnetic noise is amplified by the beam itself. (iii) The reflections from both ends of the interaction region cause an interference effect of the two bouncing waves. This in turn is revealed as a frequency selection process namely, energy in certain frequencies is preferentially transmitted forward.

The tools for the understanding of this model were developed during 1991. We have developed a model for the interaction in a TWT based on a single particle equation of motion (macro-particle model). This allowed us to show the wide energy spread in the interaction process - when reflections were ignored. As indicated above, this velocity spread can generate a wide noise spectrum in a broadband periodic structure. Once this noise generation was understood the remainder was a straight forward analysis of a linear system fed by a signal and noise. It was quite evident at this point that the usual approach in which the reflections are neglected when describing amplifiers is not adequate. Furthermore the frequency selection (interference effect) associated with this process clearly resembles the operation of an oscillator. For these two reasons we developed a model which in addition to the variation in space(1D) and in time of the amplitude of the electromagnetic field, takes into account the feedback due to reflections. This is represented by an equation which relates the amplitude at the input end at any time with the amplitude at the output end delayed by the time it takes the electromagnetic energy to travel one length of the structure. Using this set of equations we were able to show how from the single frequency operation (no noise) symmetrical sidebands can occur due to the reflection process alone. If the induced noise is taken into account then asymmetric sidebands can occur.

Narrow Band Structure(NBS).

The time it takes the wave which is reflected from the output end to reach the input is determined primarily by the energy velocity - which is the ratio between the average power flowing in the system and the average energy stored per unit length. Therefore, one can design a structure which has a low energy velocity such that by the time the first reflection approaches the input the electron pulse has ended. An alternative way to describe this process is based on the dispersion curve of a periodic structure. If the pass band is wide (say $1.5GHz$ as in our original experiments) then if the velocity spectrum of the electrons is between $0.8c$ and c, the noise spectrum is about $300MHz$. If we now design a structure which has an entire pass-band of $200MHz$ then the noise can be emitted at most in a range of $30MHz$. In other words the noise spectrum and the signal overlap so no sidebands will occur. Such a structure was designed and tested. The gain per unit length is typically $6dB/cm$ compared to $1dB/cm$ in the original structures. The efficiency can be as high as 50% but the electric field on the disk loaded structure exceeds $200MV/m$ for power levels of more than $200MW$.
The detailed experimental results were given earlier in this report. Here we wish to point out three facts: (i) as designed, the NBS has solved the problem of the broad spectrum and we are now in position to extract more than $150MW$ in a frequency range which is less than $50MHz$. (ii) The structure has a very high shunt impedance. This is

$$Z_{sh} = \frac{E_z^2(R_b)\pi R_{int}^2}{2P} \quad , \tag{1}$$

the ratio between the square of the electric field felt by the beam and the power which flows in the system. Accordingly very high fields can develop in the system which may cause, if the guiding magnetic field is not sufficiently high, electrons to flow to the walls and thus the beam breaks up. The advantage is on high gain and efficiency. (iii) Both in simulations and in experiment it seems to be very difficult to feed power into or extract power from the system. It is last aspect we started to investigate and we report next.

Passive and Active Quasi-Periodic Structures.

The way the power is injected in or extracted from the structure can become crucial in high power sources. To address this we shall treat the narrow band structure as a set of coupled cavities. Therefore the coupling of power in has to be addressed in a similar way that power is injected into a cavity. As in a klystron, if the injected power is not sufficient the efficiency is very low. The extraction region is even more important because one has to extract high power levels without affecting significantly the frequency spectrum and with minimum reflections. For this reason we initiated a study of the beam-wave interaction in quasi-periodic structures. These include structures of several cells of periodic structure with one or two transition regions. The system which models the actual structure consists of a set of coupled cavities of various external radius and length but all have the same internal radius. The coupling, which is determined by the length of the drift tube between each two cavities, can be arbitrary. Power is coupled in and out with radial arms. The first step in our investigation was to locate the optimum position of these arms. Fig. 10 shows the geometry of the narrow band structure with 9 cavities and two arms. In the first case the arms are $6mm$ from the first cells and we observe that the average transmission coefficient is $-20dB$. When the drift region was shortened to $1mm$ the transmission coefficient increases dramatically to an average value of $-3dB$. By small variations in the parameters one can control the frequency at which the transmission is $0dB$.

Let us now assume for a moment that we have matched the cold system. We know that in the narrow band structure very high gradients develop in the interaction process. In order to avoid rf breakdown we want to increase the volume where the electromagnetic energy is stored and by that we lower the energy density and consequently the field. We started with a "linear" tapering of the external radius of the cavities. We have looked for a range of parameters to bring the transmission coefficient to $0dB$ at one frequency-fig. 11. With no particular design the best we could achieve was $-6dB$ which is not acceptable. At this stage we can utilize the information gained from a preliminary analysis with dielectrics namely, that the resonance frequency of each cavity should be kept close to that of the cavities in the uniform structure. Based on this conclusion, we doubled the external radius of the last two cavities. After some fine tuning we obtained the transmission which is optimized to the required frequency - see last frame in fig 11.

Summary

(1) We believe to have a good understanding of the interaction in an <u>uniform</u> slow wave structure.

(2) Both the experimental and theoretical results indicate that we were able to eliminate the sidebands problem.

(3) In the near future we intend to direct our main effort toward investigation of quasi-periodic structures. This will be a crucial part for coupling efficiently the power from an microwave high power TWT to an accelerator system we are planning. A more thorough investigation of the interaction in these transition regions will contribute to a better conversion of kinetic energy (modulation) to electromagnetic radiation. We anticipate that proper design of such convertor will solve the problem of phase fluctuations in the output signal. We believe that this is a result of beating of the space charge mode with the electromagnetic mode in the output region.

<u>Electron Beam Modulator</u>

As described in our recent proposal we have initiated a program to develop a compact repetitive electron beam modulator capable of operating at about 1-2 pulses per second at an output voltage of up to 500 kV and at a beam current of up to 1 kA. The first stage of the device has been tested up to 120 kV and with tuning gives a 150 nsec flat top pulse with a ripple of less than 1%. We are in the process of testing a two stage device to take the output voltage up to 250 kV. This device will have, at rated voltage, to operate under oil to prevent breakdown. Each stage of the device is a 3:1 step up transformer using ferrite loaded RG8U cable for the winding. In our current tests we pulse the primary at 40 kV using a 20 Ω artificial Blumlein. The Blumlein arrangement is the opposite of that usually employed and has the center conductor grounded through a tuned LC circuit. The tuning element is designed to match oscillations in the output of the transformer due to non linearities in the ferrite cores. As may be seen in fig. 12 the tuning reduces the output ripple to less than 1%. A test stand for the pulser has been fabricated and testing at 120 kV will commence in the early summer. In addition to the modulator we have already built (several years ago) a small diameter (5 cm) magnetic field solenoid capable of producing a 6 kG field at 1 or 2 pulses per second. We shall combine these two devices in the test stand to give an electron beam facility suitable for the repetition rate mode of operation needed for a practical device. At present we have fabricated and tested two 120 kV single stage transformers, the field coil system, and a diode shell.

CONCLUSIONS

Over the last year we have made substantial progress in our research on intense and coherent microwave sources. This work has resulted in the development of a single frequency coherent wave generator at 9.0 GHz with an output power of about 200 MW. Results have been confirmed using a new calorimeter diagnostic and are consistent with simulation data obtained using the MAGIC code. A paper is in preparation describing these recent advances.

Work is progressing on the development of a repetitive source facility and the first stage should be on line during the summer, with an upgrade to 250 kV expected within a year.

Measurements of the energy spread in the electron beam after microwave generation using the NBS have been inconclusive, due in part to poor choice of a null experiment. Work is in progress to repeat the measurements with a better choice of the null experiment. We have in the meantime redesigned the spectrometer to improve the detection sensitivity for higher energy electron resolution.

A listing of the journal and conference papers arising from this work is appended to the report.

REFEREED JOURNAL AND CONFERENCE PAPERS

1. "Slow-wave amplifiers and oscillators: A unified study," Levi Schächter and J. A. Nation, *Phys. Rev. A*, **45**, 12, 8820, 15 Jun 1992.

2. "Neutralization and transport of high current proton beams in a two stage linear induction accelerator," Cz. Golkowski, G. S. Kerslick, J.A. Nation and J. Ivers, *J. Appl. Phys.*, **71**, 6, 2570, 15 Mar 1992.

3. "Narrow Pass-Band High Power TWT Amplifier," Levi Schächter and J. A. Nation. Presented at the 3rd Workshop on Advanced Accelerator Concepts, Port Jefferson, NY, 14-20 June, 1992.

4. "High power x-band microwave amplifiers and their application for particle acceleration," T. J. Davis, J. D. Ivers, G. S. Kerslick, E. Kuang, J. A. Nation, M. Oppenheim, and L. Schächter. Presented at the 9th International Conference on High-Power Particle Beams, Washington, DC, May 25-29, 1992.

5. "High Power TWT Amplifier Research for Electron Accelerators," J. A. Nation, L. Schächter, E. Kuang and G. S. Kerslick. Proceedings of the 3rd International Particle Accelerator Conference, Hamburg, July 1992.

6. "An Electron Injector Based on a high Power X-Band TWT Amplifier," L. Schächter, J. A. Nation, G. S. Kerslick and J. D. Ivers. Presented at the 3rd Workshop on Advanced Accelerator Concepts, Port Jefferson, NY, 14-20 June, 1992.

7. "A proposed extended cavity for coaxial relativistic klystrons," L. Schächter, T. J. Davis and J. A. Nation. Presented at the 9th International Conference on High-Power Particle Beams, Washington, DC, May 25-29, 1992.

8. "Microwave amplifiers and oscillators: A unified study," L. Schächter, and J. A. Nation. Proceedings of SPIE Vol.1629: Intense Microwave and Particle Beams III p.81.

9. "Integrated amplifier and accelerator system," L. Schächter, and J. A. Nation. Proceedings of SPIE Vol.1629: Intense Microwave and Particle Beams III p.470.

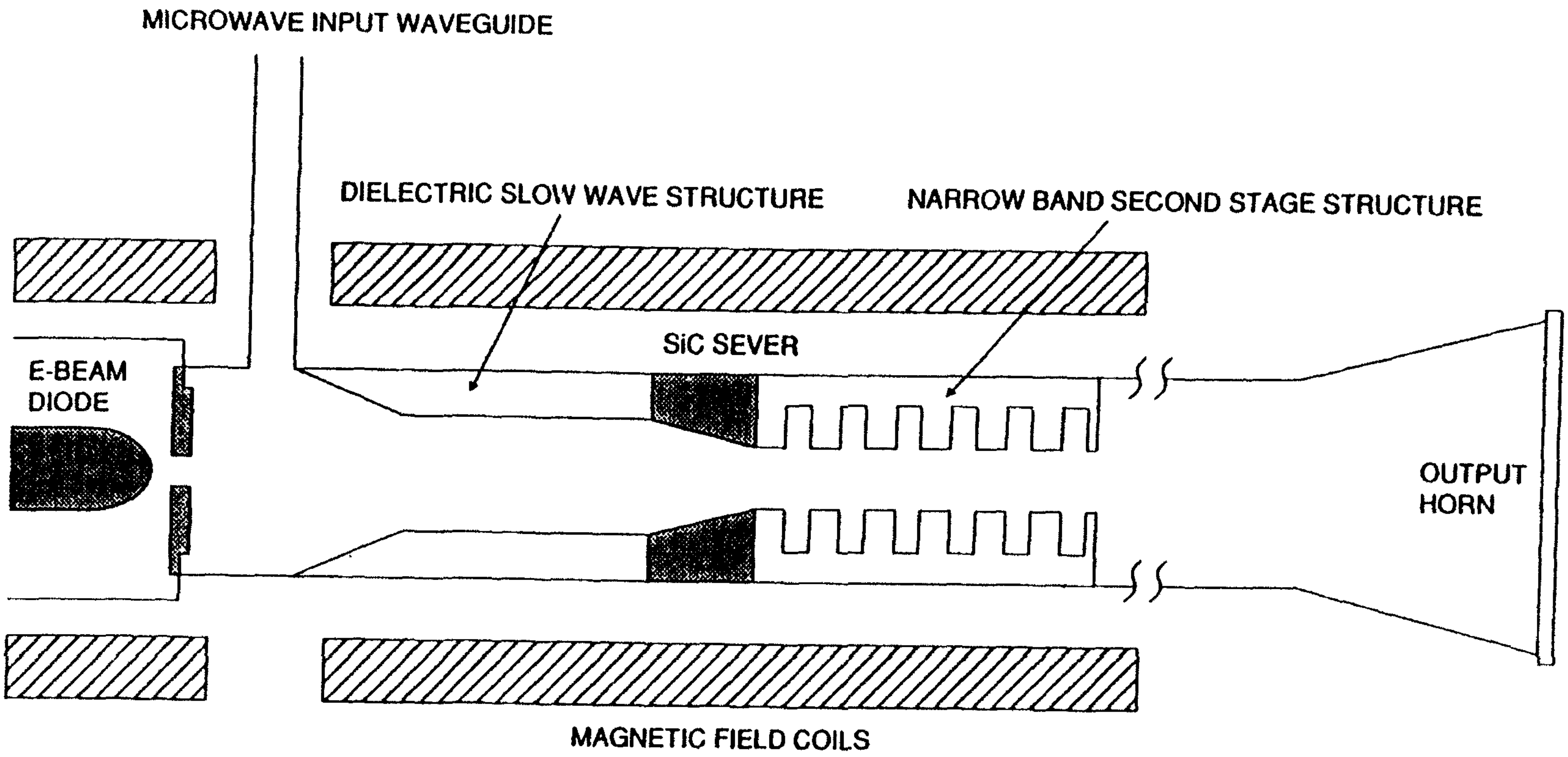
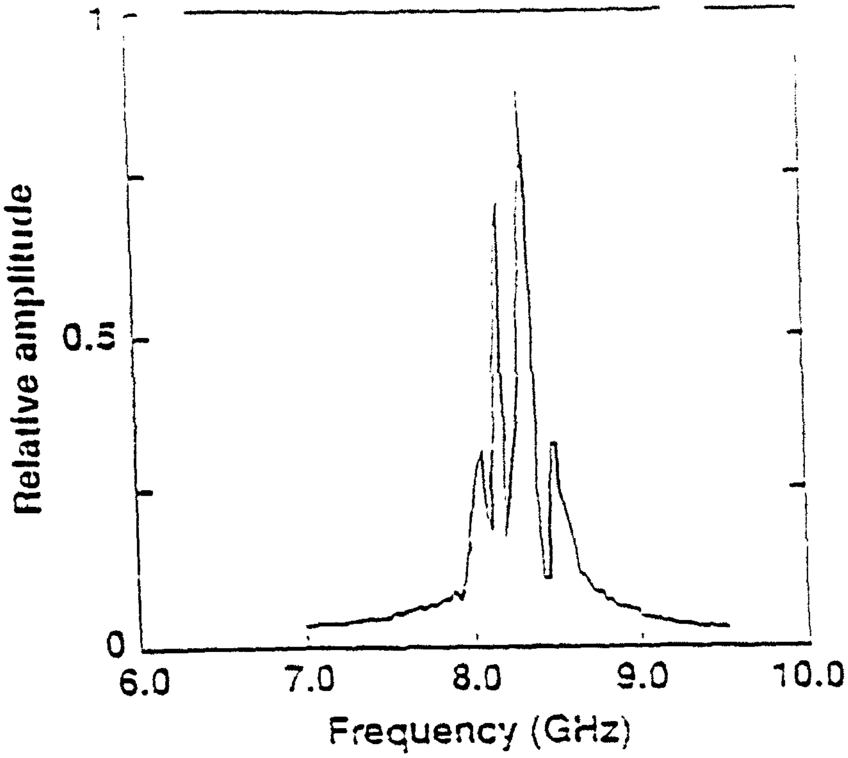


Fig. 1 Schematic diagram of the two stage narrow band structure (NBS).



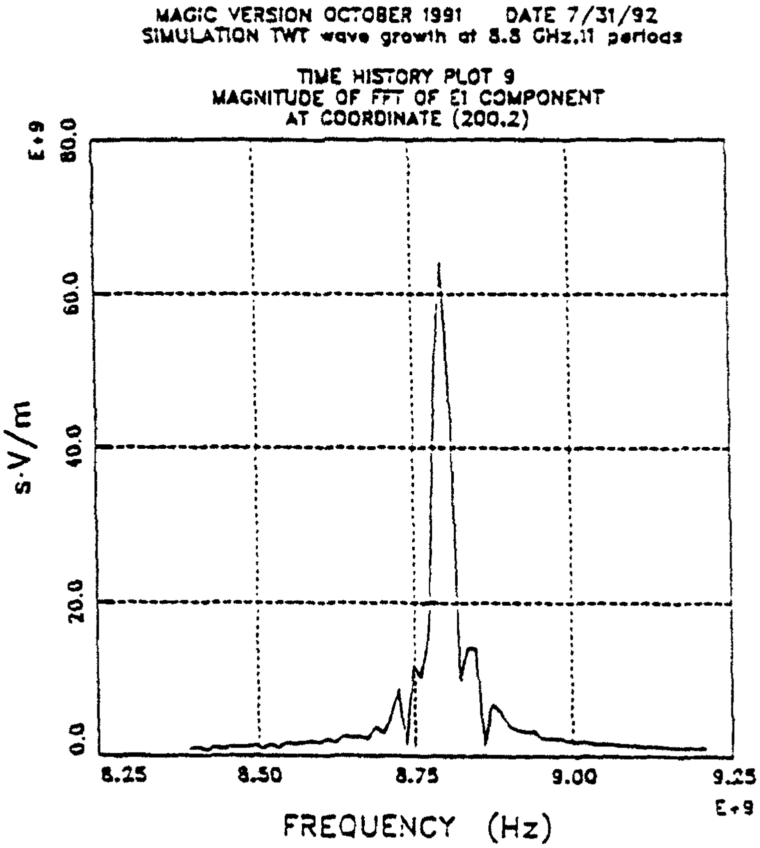
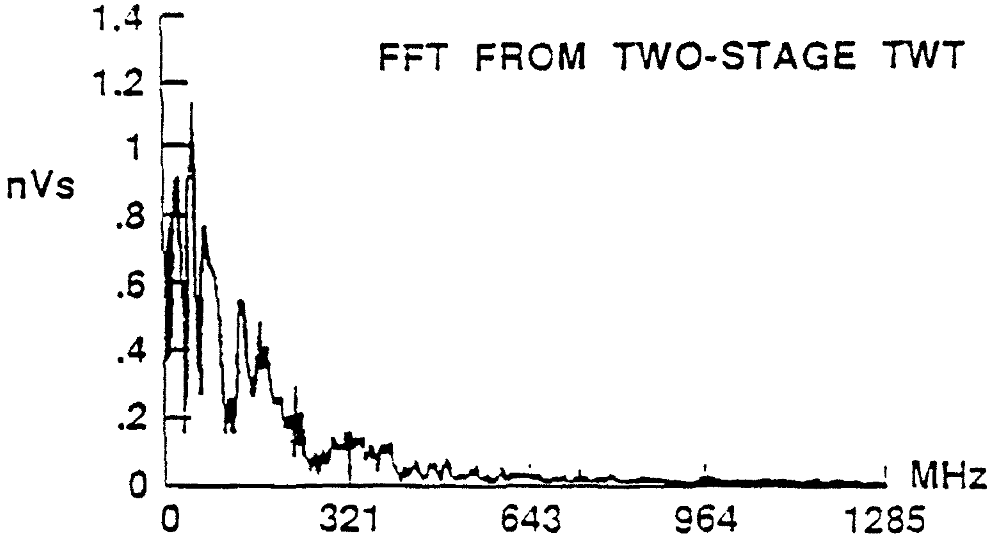


Fig. 2 MAGIC code results showing the output FFT from the 1.7 GHz passband structure (upper trace) and the 400 MHz narrow band structure.



Fast Fourier Transform
Severed TWT
900 A

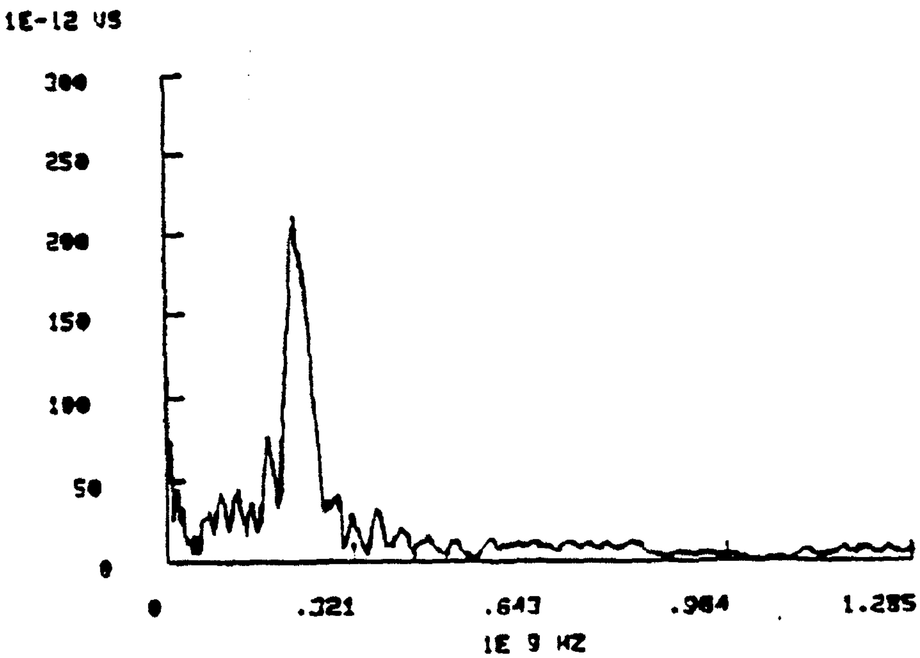


Fig. 3 Experimental FFT results showing output from the 1.7 GHz passband two-stage, severed TWT (upper trace) and output from the narrow band structure. The absence of sidebands in the second device is clearly shown in this comparison.

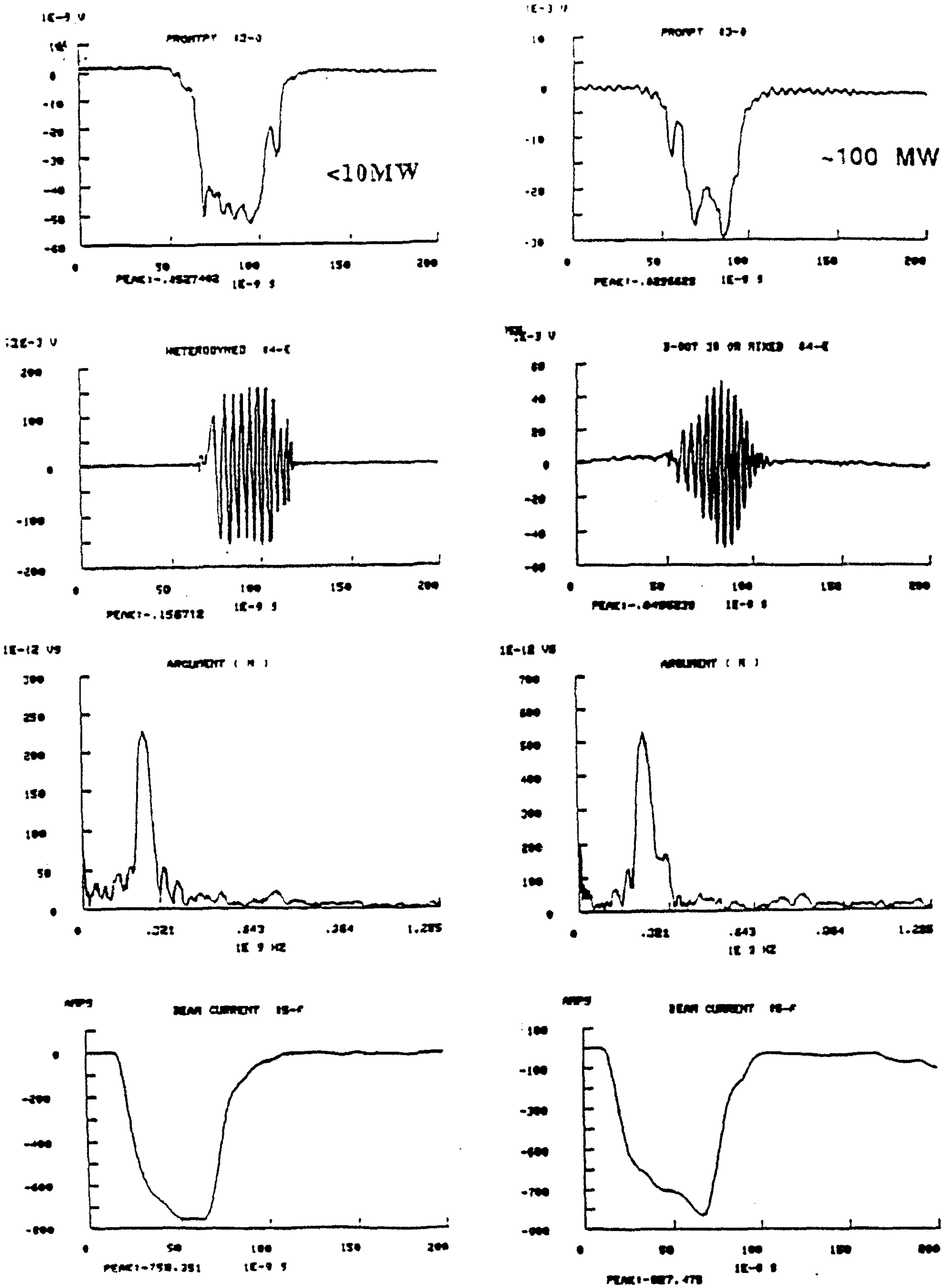


Fig. 4 Experimental waveforms from the narrow band structure at two output power levels. It should be noted that for the 1.7 GHz passband structures sidebands are always present at output powers > 70 MW.

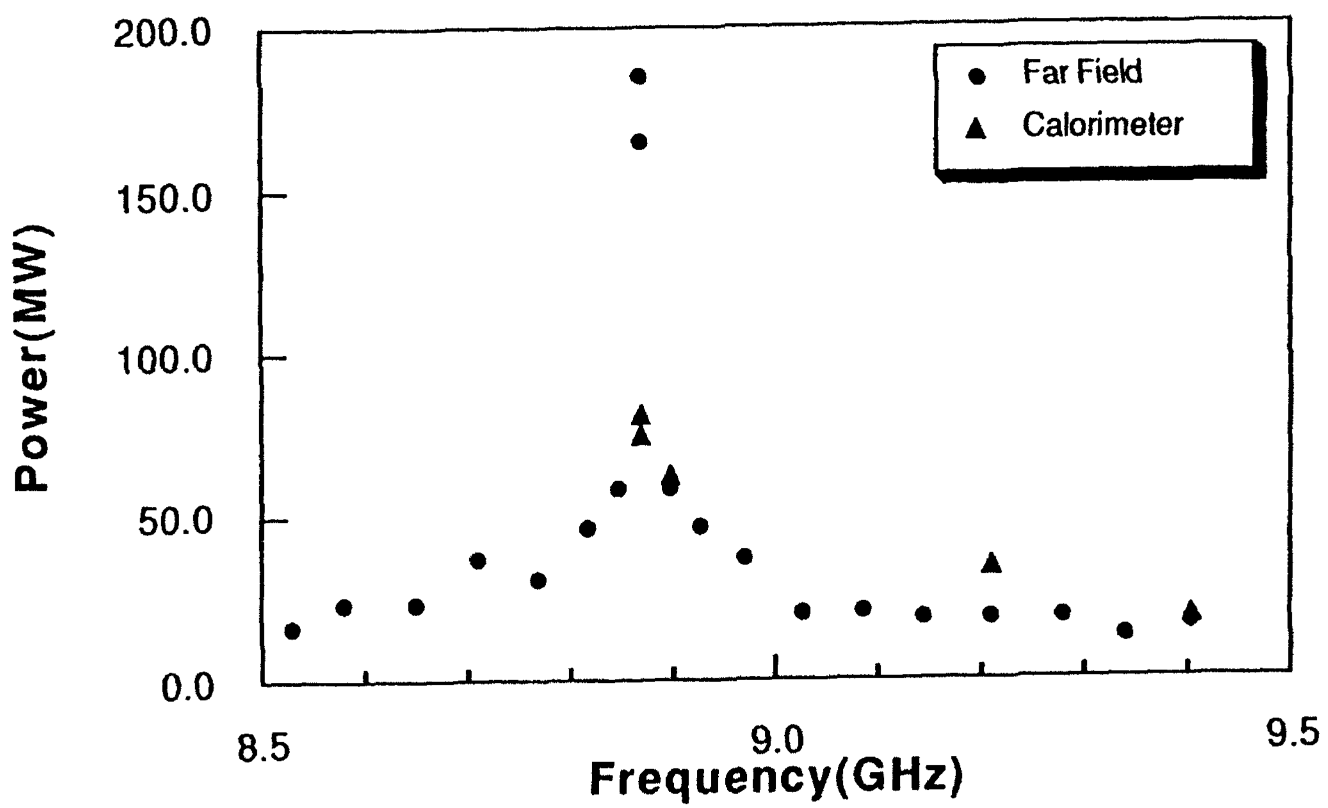


Fig. 5 Gain bandwidth for the two stage narrow band structure. The microwave pulse width is normalized to 40 nsec for all shots. Note that the calorimeter pressure transducer appears to saturate at an incident power level of around 65 MW.

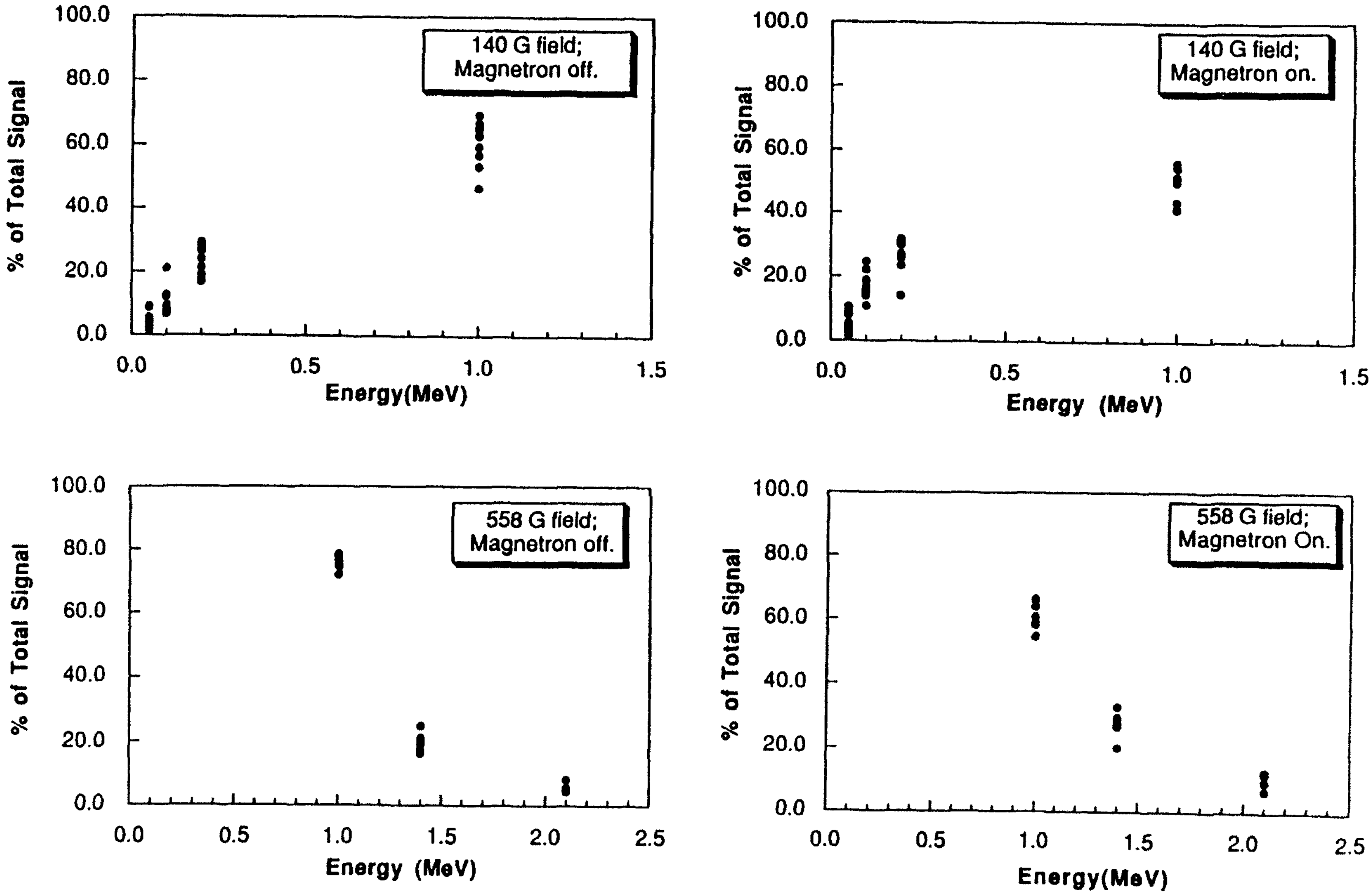


Fig. 6 Electron energy spectra for two values of deflection field. In both cases there is an increased energy spread when the rf power is on.

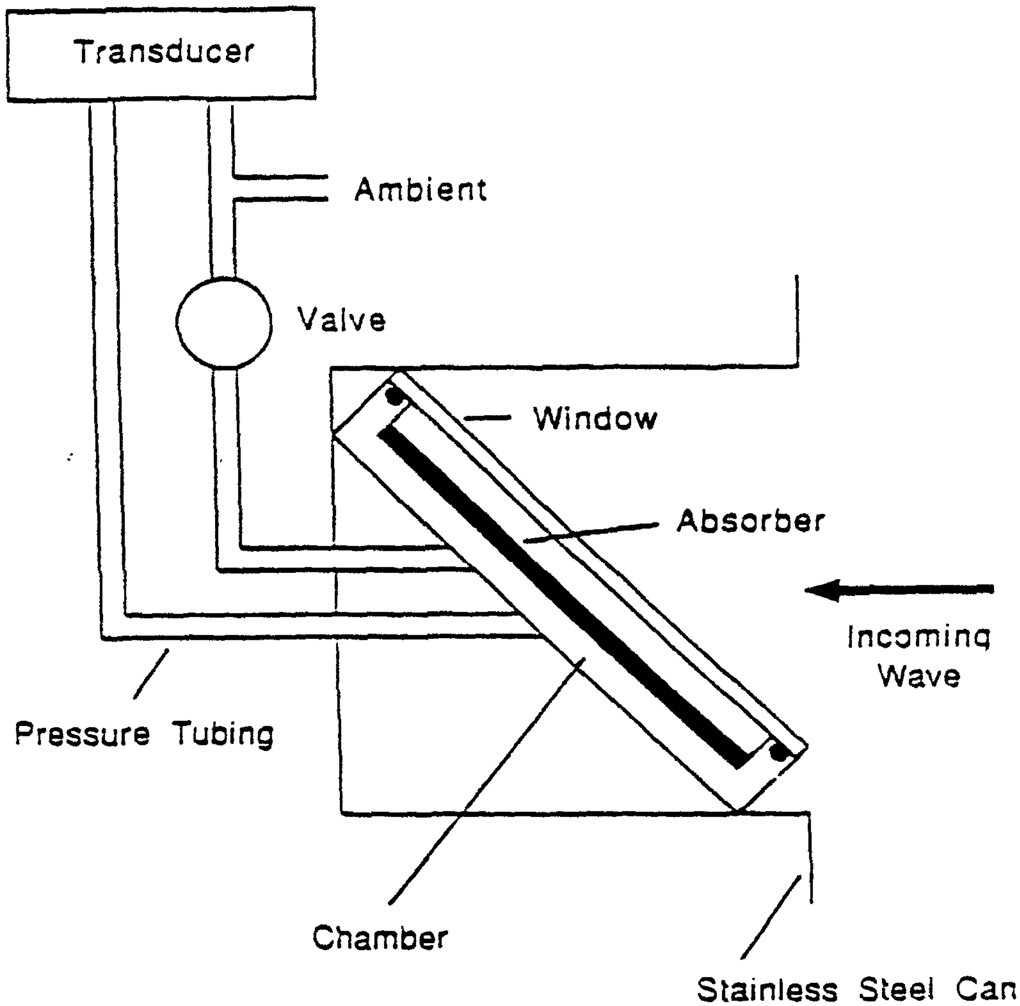
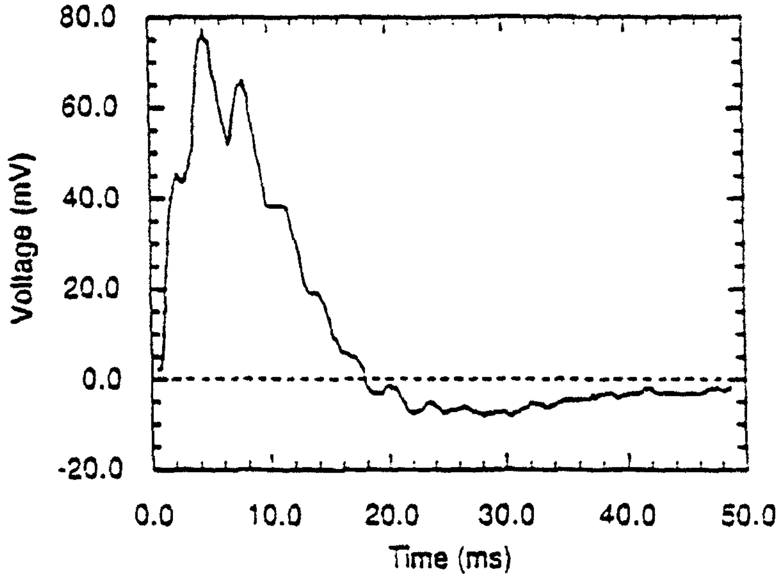


Fig. 7 Schematic showing assembly of the calorimeter for measuring high microwave power levels.



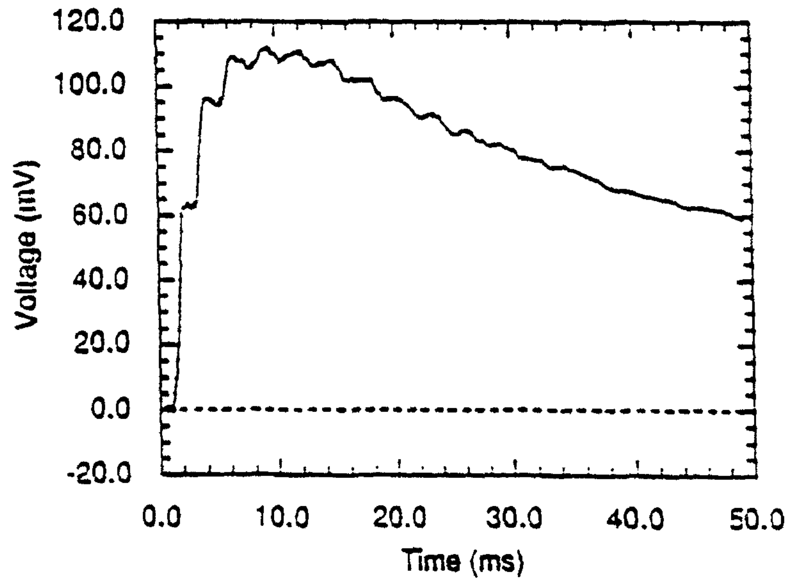


Fig. 8 Typical waveforms from the calorimeter comparing a control shot, with valve open, at 9.0 GHz (upper trace) with a single pulse calibration shot, with valve closed (lower trace). The calibration figure is measured at 25 msec giving enough time for the decay of transient effects.

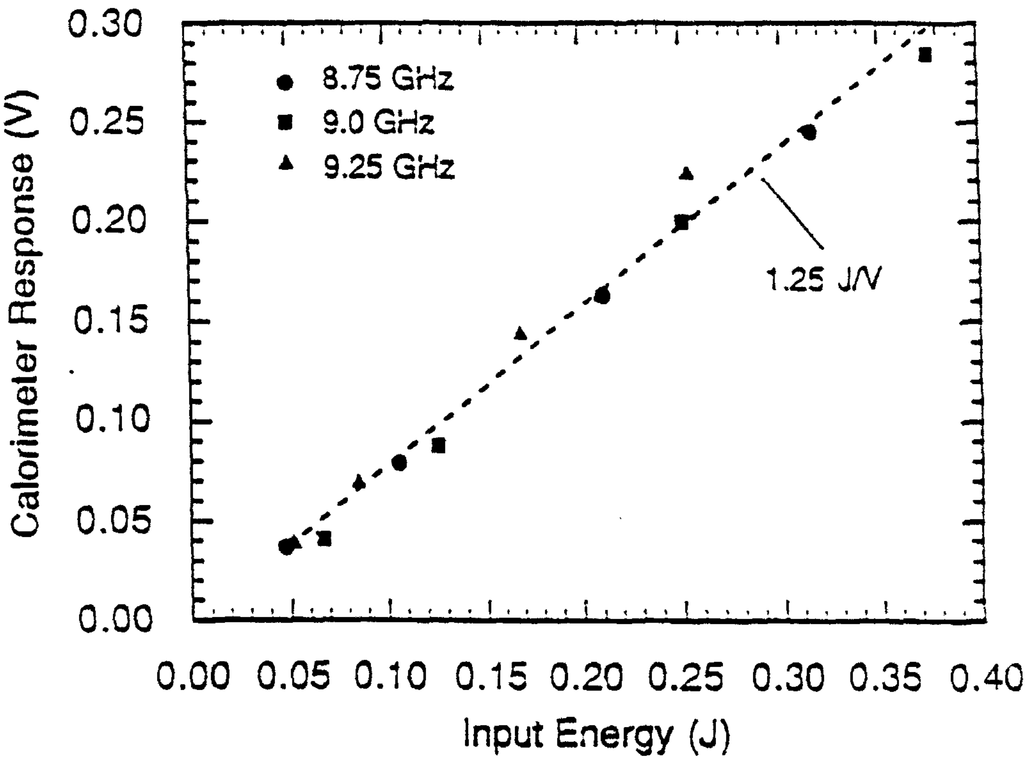


Fig. 9 Complete calibration data for the calorimeter. Linear response is obtained over the range of input energy levels shown and no significant variation is observed at different frequencies.

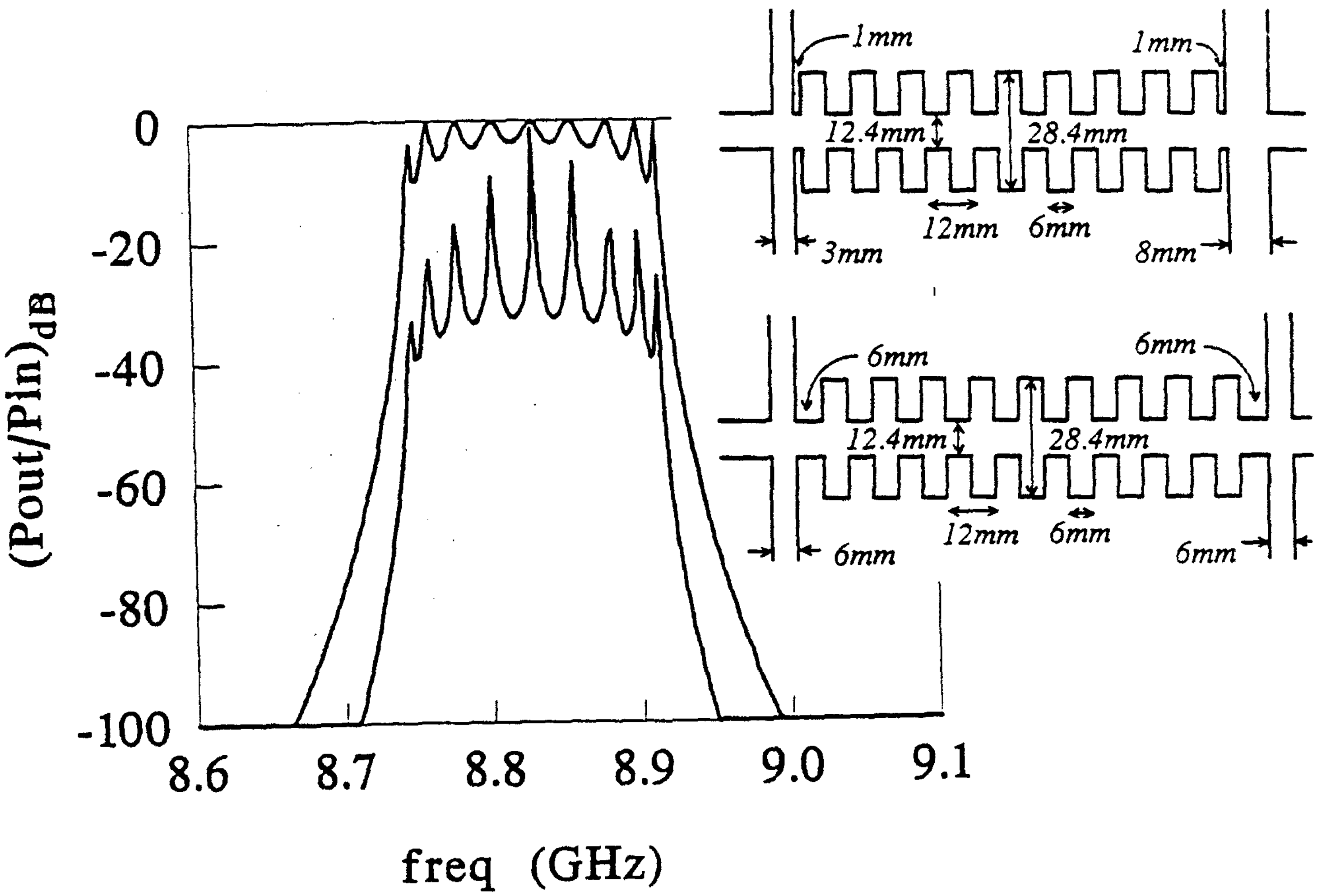


Fig. 10 The transmission coefficient of a disk loaded structure with radial arms. When the arms are $6mm$ apart from the first cavity the transmission is typically by $20dB$ down compared to the case when they are $1mm$ apart.

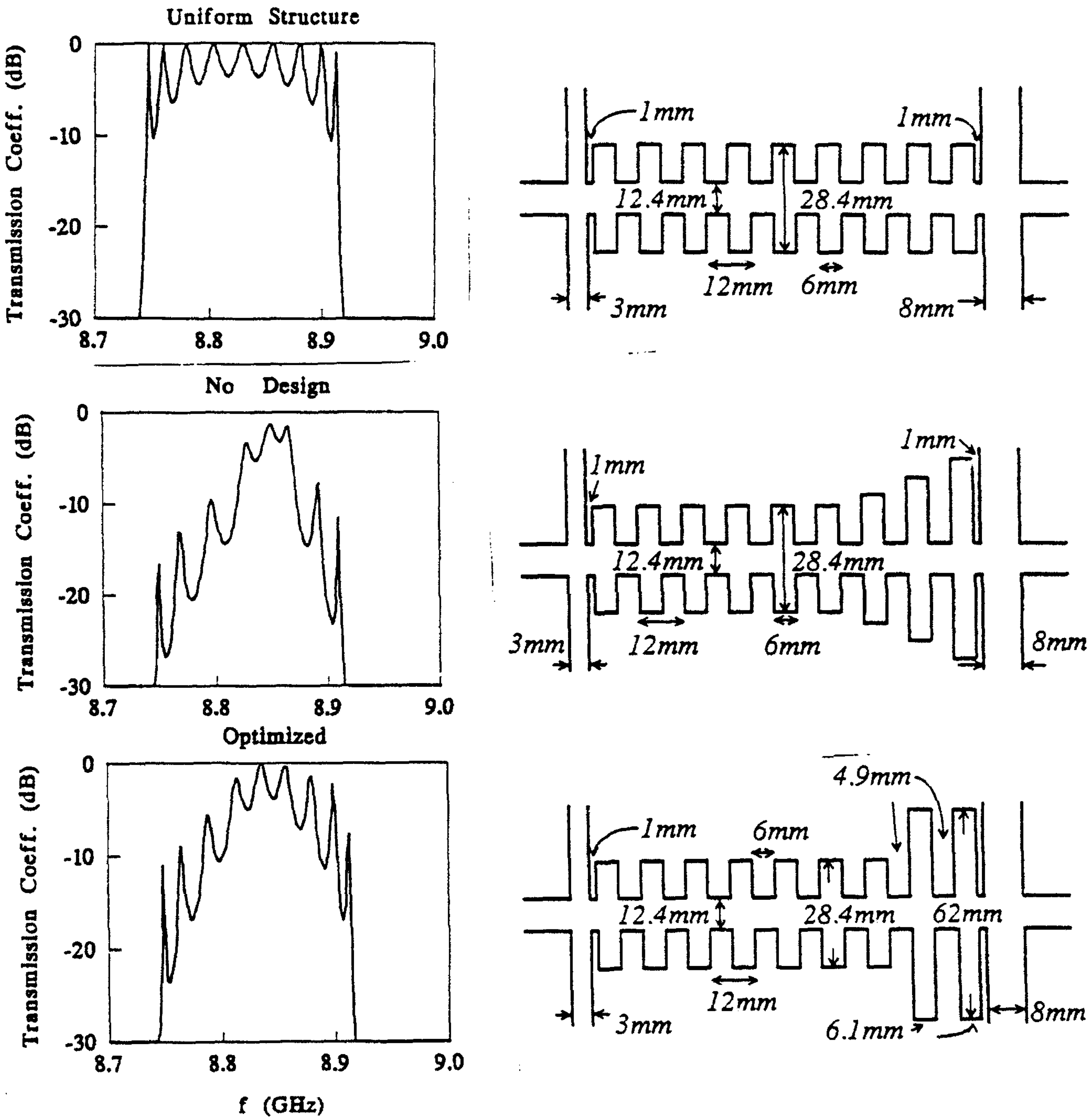


Fig. 11 Cold structure optimization with the constraint of increasing the volume of the last cells to avoid rf breakdown and beam break-up. The optimization is obtained when the geometry of the cells is such that the resonance frequency is maintained (second mode).

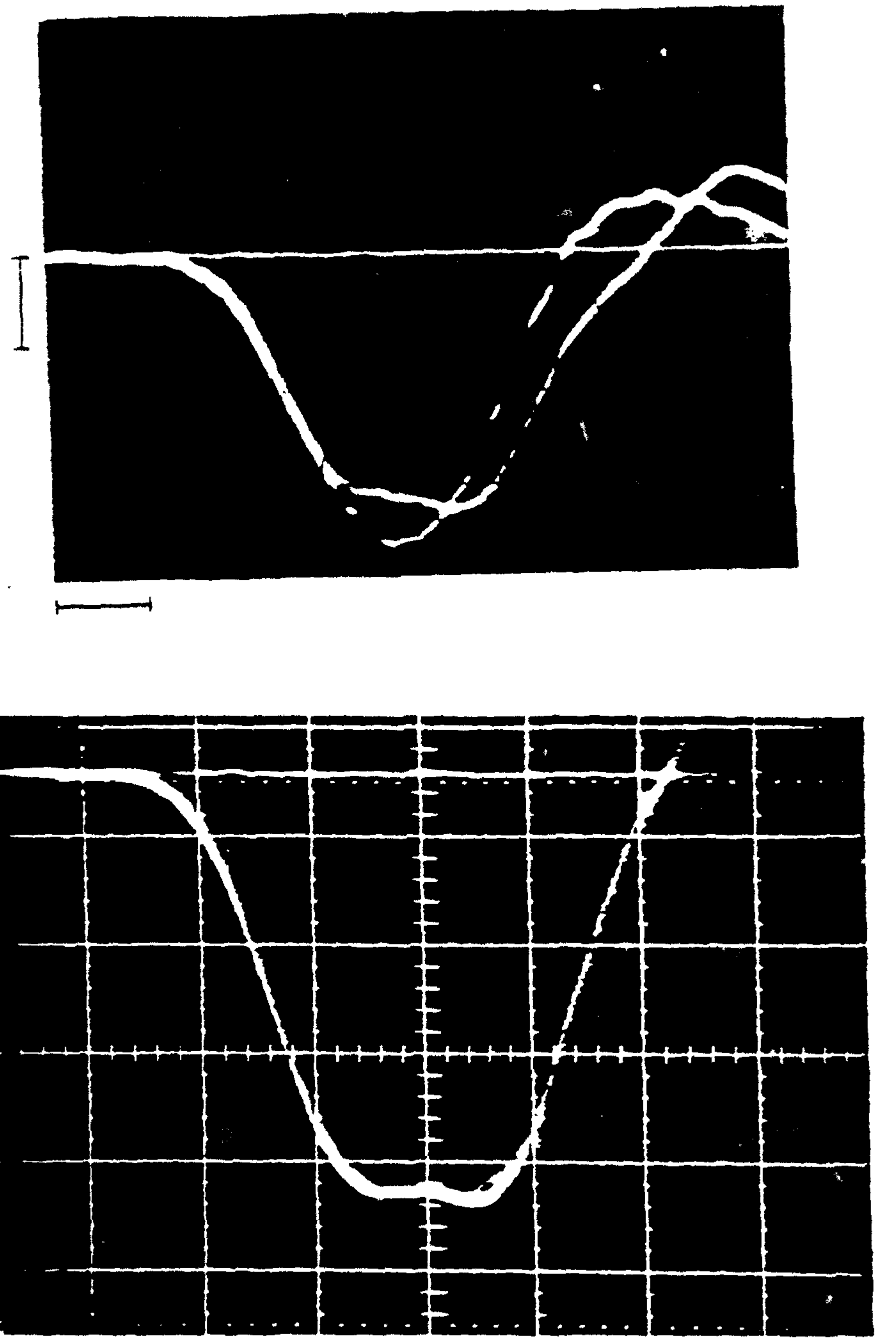


Fig. 12 Modulator output voltage traces. Upper traces are with 230 Ohm load, lower traces are with 500 Ohm load and optimized tuning LC circuit. Scales are 23 kV/div and 50 nsec/div.